Extended Measurements in Bering Strait
and
The Variable Outflow from the Chukchi Shelf to the Arctic Ocean
and
An Extended Analysis of Time Series and Hydrographic Data with Reference to Shelf-Basin Interactions

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Award #: N00014-99-1-0345
and
Award #: N00014-02-1-0305
and
Award #: N00014-99-1-0321
http://psc.apl.washington.edu/HLD/

LONG-TERM GOALS

Our long-term research goals are to understand the circulation and physical properties of the high-latitude ocean, both quantitatively and mechanistically. We also seek to understand the effects of physical processes in the ocean on the ice cover, biology, and chemistry of the marine environment. The variability of that environment is a special focus and concern.

OBJECTIVES

Our three major objectives are closely related, reflecting the three grants on which we are reporting.

Our first objective is to extend direct measurements of velocity, temperature, and salinity in Bering Strait, supplemented by time series measurements of ice-thickness and of *in situ* nutrients and related optical properties using upward-looking sonars, nutrient analyzers, and other sensors. This upstream information is vital to the Shelf-Basin Interaction (SBI) initiative, since the influx of Pacific waters provides a key forcing for the western Arctic shelf-slope-basin system, including its biogeochemistry. A particularly important dynamical aspect of the Pacific water presence in the Arctic Ocean is its contribution to stabilizing the upper ocean, thereby influencing heat flux and ice thickness.

Our second objective is to make moored measurements of velocity, temperature, salinity, and ice drift in the northern Chukchi Sea during 2002-2004 in support of SBI Phase 2. These time series are being supplemented by hydrographic sections. Our focus is on the transformation and outflow from the shelf of Pacific waters that have entered through Bering Strait, and also on providing a context in which both the SBI process studies and the downstream Beaufort moored measurements can be embedded.

Our third objective is to analyze earlier data from the western Arctic, and especially the Chukchi Sea, to ascertain the variability of the shelf-basin system; to identify, and where possible quantify, the important physical mechanisms controlling this system; to contribute to the SBI goals by illuminating the mechanisms of shelf-basin exchange; and to promote further improvements in the rapidly growing array of models of arctic circulation, hydrographic structures, and variability by providing data suitable for boundary conditions and model verification.

APPROACH

We are maintaining instrumented moorings in Bering Strait; and in conjunction with earlier measurements, these provide nearly continuous records of flow and water properties in the strait over more than a decade. Velocity, temperature, and salinity are the core physical measurements at each mooring, supplemented with ice thickness measurements using upward-looking sonar, *in situ* nutrient determinations, and optical measurements (cf., the related project section). Two moorings are being maintained in the eastern channel, while a third mooring north of the Diomede Islands, just east of the Russian EEZ, serves as a proxy for the western channel. Together with extensive shipborne hydrographic and ADCP measurements made each year, this instrumented array provides information on the temporal and spatial variability of the flow and water properties in the strait.

Together with T. Weingartner (University of Alaska) we are making moored time series measurements within the primary throughflows on the northern Chukchi shelf [Barrow Canyon (ca. 80 m depth), the Central Channel (ca. 50 m), and on the north-central shelf downstream of Herald Valley (ca. 70 m and 110 m)]. The moorings include current meters (both fixed-depth and profiling, the latter with bottom tracking to measure ice drift) and temperature/conductivity recorders. In a closely related effort, R. Pickart (WHOI) is maintaining a mesoscale array on the Beaufort slope near 152°W, and J. Swift (SIO) is providing CTD/rosette sections to support the mooring work. The sections also include ADCP measurements that provide detailed spatial information on the velocity field. Data will be shared with other SBI investigators after calibration and data quality assurance, and will also be submitted to the appropriate data centers in a timely manner.

Together with Weingartner we are also analyzing and synthesizing earlier moored time series and hydrographic data from the western Arctic, and especially the Chukchi Sea. This work addresses the circulation and water properties, with emphasis on their variability, especially seasonal and interannual, and on the principal processes and dynamics governing the system.

WORK COMPLETED

The three Bering Strait moorings deployed in 2002 were recovered this past July from the *R/V Alpha Helix*, and three new ones were deployed. These moorings incorporate instruments for measuring velocity, temperature, salinity, ice thickness, nutrients, fluorescence, and transmissivity. Additionally, extensive CTD and ADCP sections were made from Bering Strait to north of Cape Lisburne. Water sampling included nutrients, O-18, and carbon constituents. (For a cruise description, cf., http://psc.apl.washington.edu/HLD/AH2003/AlphaHelix2003.htm.)

The four UAF/UW moorings on the northern Chukchi shelf installed last summer have just this September been recovered from the *USCGC Healy*, and four new ones have been deployed. The mooring work is being supplemented by hydrographic sections, and these will be completed by 30 September, after which the Healy will move into the Beaufort for related SBI work.

We have also continued the analysis of earlier data from the western Arctic, and results have been reported at several national meetings. A journal paper, dealing with the central Chukchi shelf circulation, will shortly be submitted to JGR. A second paper nearing completion examines the Chukchi Sea in its entirety, with respect both to circulation and water mass modification, and is based on a synoptic data set.

RESULTS

The monthly mean temperature, salinity, and throughflow speed in Bering Strait from 1990-2002 are shown in Figure 1. Recent years continue to be cool, much like the early 1990s. This is in marked contrast to the extremely warm period of the mid-1990s, which was accompanied by major changes in the ecosystem. Overall, the salinity record of Figure 1 is complex, with large interannual variations and with multiple extrema in some years, e.g., 1998. Such variations will be transmitted into the halocline of the Arctic Ocean, where they modify upper ocean stability. Rather than a relatively simple annual salinity cycle in Bering Strait that is forced by the competing effects of freezing and of precipitation and runoff, our measurements suggest that advective changes also are first-order effects. This implies that the regional salinity distribution and circulation in the Bering Sea is a determining factor in the variability of the Pacific injection into the Arctic Ocean. Finally, we note that the velocity record shows a marked annual cycle, with strong inflow in summer and weaker flow in winter, but that there are no clear long-term trends or transitions in the inflow rate over the 12-year period.

The first-year moorings from the northern Chukchi are still at sea, and examination of the records awaits return and calibration of the instruments. The hydrographic sections from the deployment cruise in 2002 show modal waters near the shelf edge that are close to the freezing point and have salinities as high as 33.4 psu, i.e., consonant with injection into the upper halocline of winter waters from the Pacific. Some of this water fluoresces strongly, corresponding to a high chlorophyll load, and turbidity is elevated near the bottom. The isopycnal inclination over the outer shelf and upper slope is consistent with eastward flow, and property distributions suggest formation of anticyclonic eddies. (Cf., www.whoi.edu/science/PO/arcticedge/arctic_west02/science/data.html and http://psc.apl.washington.edu/HLD/SBI2003/SBIHealy2003.html.)

Our analysis of earlier measurements shows that the generally northward flow from Bering Strait across the Chukchi Sea crosses the northern shelf through three conduits: Herald Valley, the Central Channel, and Barrow Canyon. The flow is particularly coherent over the southern portion of these paths, from Bering Strait to the central Chukchi. Correlation length scales in the Chukchi Sea are in general much greater than the local Rossby radius, and are probably set by the atmosphere, with the wind providing first-order forcing for the ocean. The correlation with the wind field is particularly apparent in Bering Strait, the central Chukchi, Barrow Canyon, and along the eastern flank of Herald Canyon. The mean residence time for Pacific waters in the Chukchi is about four months, but is much longer in winter than summer, corresponding to the stronger northerly winds and weaker currents during winter. This large seasonal variability likely has major consequences for the shelf ecosystem, e.g., for nutrient cycling. Winter water mass modification over the Chukchi shelf depends on the fall and winter winds, which control the seasonal evolution of the ice. For example, an extensive ice cover during fall reduces cooling, limits new ice formation, and results in little salinization of the water column. In such years, Bering shelf waters cross the Chukchi with little modification, even along the Alaskan coast. On the other hand, extensive open water in fall leads to early and rapid cooling, and if accompanied by vigorous ice production within coastal polynyas, results in the production of high-salinity waters in the eastern Chukchi. Such interannual variability likely affects mixing processes over the slope and the depth at which Pacific waters intrude into the Arctic Ocean interior.

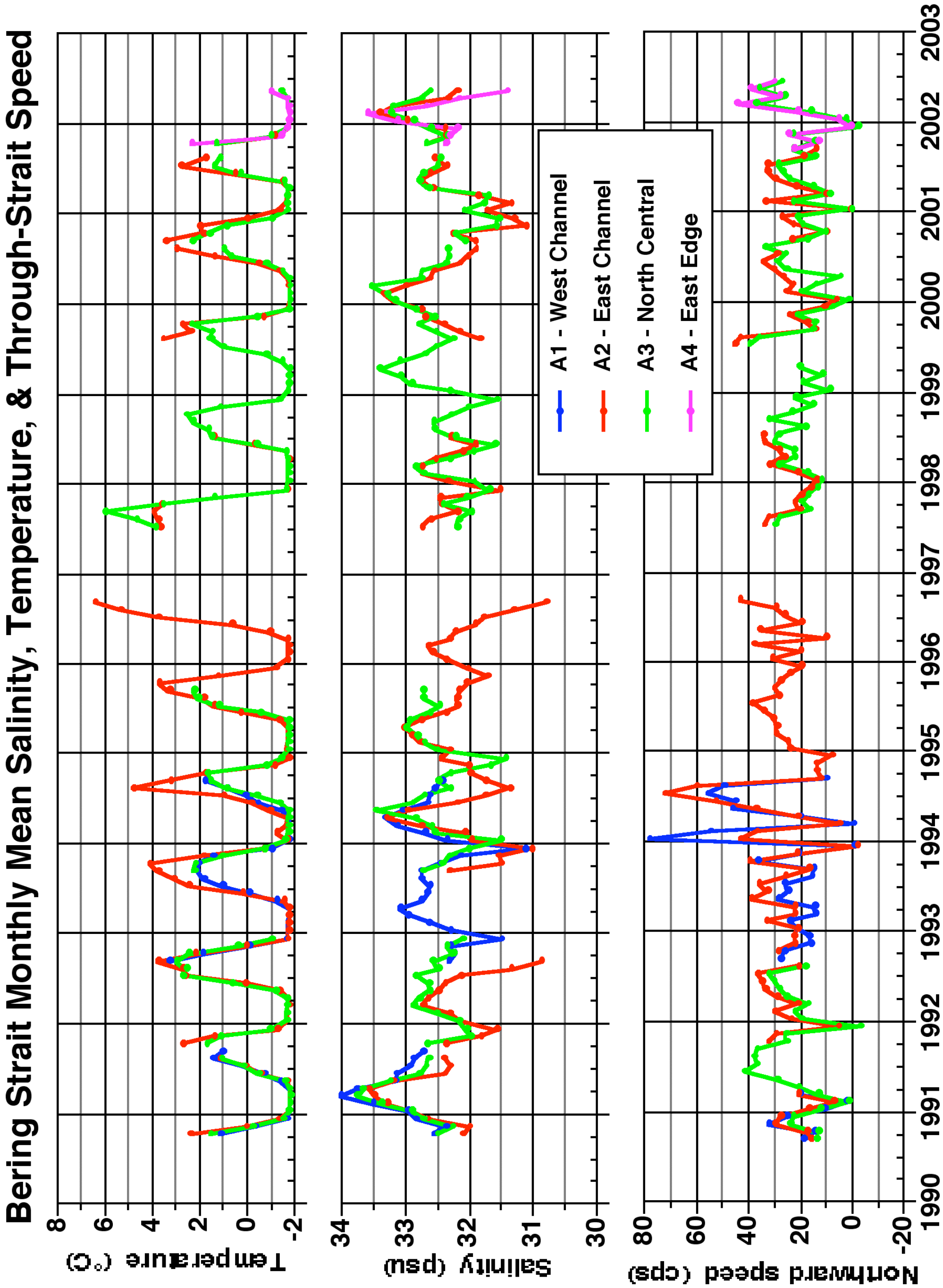

Figure 1: Monthly mean temperature (top), salinity (middle), and throughflow speed (lower) in Bering Strait during 1990-2002. Moorings A1 and A2 respectively measure the middle of the western and eastern channels; A3, located just north of the center of strait, shows characteristics of both channels; and A4 represents the easternmost part of the strait, where a coastal jet is sometimes found.

IMPACT/APPLICATIONS

Major goals of the SBI initiative are to understand the physical processes responsible for water mass modification over the arctic shelves and slopes and for the exchanges with the interior ocean, as well as to understand the variability of these systems. All three of our reported projects address these goals directly. In particular, we seek to quantify the large variability found in the Pacific-origin waters that flush the western Arctic shelves. Much of this variability is generated in the Bering Sea, although the northward-flowing waters may in some years be further modified in the Chukchi, particularly during winter along the Alaskan coast. The shelf waters are subsequently discharged into the Arctic Ocean, where their seasonal and interannual variability are propagated, in part by eddies that drift into the interior and in part by boundary currents that rim both the Polar Basin and its major ridge structures. This propagation leads to variability in regions far from the originating shelves. An understanding of these effects and processes will be vital to future conceptualizations and models of the Arctic Ocean.

The accumulating time series from Bering Strait, now more than a decade long, provides a remarkable record of the upstream forcing of the Chukchi shelf, and ultimately of the Arctic Ocean halocline. The very high salinities at the beginning of the 1990s have not returned to Bering Strait, nor has there been a return to the anomalously warm conditions of 1996-1997. Rather, recent years have seen an alteration between fresh and moderately saline regimes, but inevitably cool. For ventilation of the Arctic Ocean halocline to be as deep as that in the early 1990s, therefore, when the Bering Strait waters were exceptionally saline, there would have to be extensive freezing downstream on the eastern Chukchi shelf, something which in turn depends on fall and winter ice and wind conditions.

Our measurements of the time-dependent shelf circulation also provides important guidance to investigations of shelf productivity and biochemical cycling. For example, water parcels leaving the northern Chukchi shelf will exhibit substantially different carbon and nutrient loading, depending on their trajectory and the season. The measurements address other prominent issues as well, including the flux and processing of freshwater on the western Arctic shelves, and the needs of a variety of arctic simulations for realistic long-term boundary conditions and for verification data.

RELATED PROJECTS

In Bering Strait we continue cooperative work with T. Whitledge, UAF, through deployment of an *in situ* nitrate analyzer and optical sensors. The latter measurements are representative of the new techniques that will be required to illuminate biogeochemical cycles in the high-latitude ocean. We also continue our cooperation with R. Moritz, UW, through deployment of upward-looking sonars to measure ice thickness. These deployments address the need for circumpolar time series measurements of ice thickness, both to illuminate issues of ice mechanics and thermodynamics and to track changes in ice thickness that may accompany those observed within the Arctic Ocean by submarines. We also support a number of other investigators in Bering Strait by providing sampling opportunities during the mooring cruises, including L. Cooper, J. Grebmeier, and C. Deal.

The SBI program on the northern Chukchi shelf is collaborative with T. Weingartner, UAF; with R. Pickart, WHOI, who is concentrating on the adjacent Beaufort shelf and slope; and with J. Swift, SIO, who is making hydrographic measurements throughout the SBI region.

Finally, our analysis of the western arctic data set is collaborative with T. Weingartner, UAF.